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Variability in Geotechnical Properties of Sediments and Dredged Materials

PURPOSE: This technical note provides an overview of selected uncertainties involved in estimating or characterizing pre-dredged sediment and dredged material geotechnical properties. Variations in geotechnical properties of dredged materials and sediments are expected to be similar to those found in typical geotechnical materials, but this technical note addresses some of the unique aspects of identifying and evaluating the variability of selected material properties before, during, and after dredging operations.

BACKGROUND: Characterizing dredged material sediment properties is a basic requirement for any proposed dredging operation, and the basic geotechnical parameters need to be measured or predicted in many cases. The most basic parameter is the material's physical property classification based on the grain size distribution of gravel, sand, silt, and clay. Other physical properties include water content, density, specific gravity, and percent solids. Engineering behavior properties such as shear strength and consolidation are also measured or predicted. Technical Note DOER-N13 (*www.wes.army.mil/el/dots/doer/*) includes a list of the most common geotechnical properties used in characterizing dredged materials.

The dredging process often involves radical manipulation of in situ sediments. Undisturbed (or previously disturbed) soil and rock deposits are ripped apart, agitated, pressurized, remolded, transported, discharged, and/or re-deposited using various dredging techniques and equipment. Dredging may be accomplished by hydraulic suction or mechanical means (or a combination of techniques), and various types of dredging platforms are available for each technique (Department of the Army 1983). Once the material is dredged, it is delivered by various techniques and equipment to its final placement (or disposal) site above or below water.

Disturbed or remolded geologic materials exhibit different engineering properties when compared to their undisturbed state (Scott 1963), and most dredged materials undergo significant remolding during transition from their in situ to final disposal states. By the time most in situ fine-grained cohesive materials have been dredged, transported, and redeposited, their original (pre-dredged) geotechnical properties may no longer be valid. Coarse-grained sediments in maintenance dredging may revert to their original properties, but even they may undergo changes in grain size distribution depending on the placement operation. The degree to which the properties have been changed depends on the techniques and equipment utilized during the dredging and placement processes as well as the changes imposed by the surrounding environment.

This technical note describes some underlying reasons for geotechnical property variability, including equipment and environment effects, in order to acquire a better understanding of the relationships between selected geotechnical properties and dredging processes. General trends in property variability were measured by obtaining and testing several dredged materials and by

reviewing examples from recently published project literature. The data are not intended to be statistically robust, but are presented to illustrate general trends in property variability.

VARIABILITY DUE TO SPATIAL LOCATION: Physical property changes within a pre-dredged, undisturbed, and heterogeneous sediment are often uncertain and difficult to predict, and when the sediment becomes disturbed, remixed, or remolded, the uncertainty becomes greater. Often the spatial variability influence is detected during sediment sampling conducted before, during, or after the dredging operation. Horizontal and vertical heterogeneities affect spatial variability. The following two examples are from the same project in Boston Harbor and serve to illustrate the changes in physical properties and engineering behavior encountered simply because of the samples' horizontal locations.

River Sediment Samples. Surficial grab samples were taken from the bottom of the Mystic River in Boston, Massachusetts, for the purpose of characterizing the geotechnical properties of material to be subsequently dredged and placed in subaqueous disposal cells located further downstream in the Mystic River and Boston Harbor. The samples were taken with small (150 cu in. or 0.0033 cu m) hand-operated bottom dredge samplers, which scooped surficial material from the channel bottom at a depth of approximately 40 ft (13.2 m). Several samples from within a 50-ft (16.5 m) radius of each of three target locations (MRA, MRB, and MRC) were withdrawn to the surface and placed in a sealed bucket. Each target location was approximately 1000 ft (330 m) apart. Myre et al. (2000) and Science Applications International Corporation (SAIC) (2000) describe the geotechnical aspects of the Boston Harbor project including the sampling methods and locations.

The upstream sample (MRA), the middle sample (MRB), and the downstream sample (MRC), were analyzed for specific gravity, grain size distribution, Atterberg limits (plastic and liquid limits), organic content, water content, vane shear strength, and consistency. Visual identification indicated a fine-grained, dark gray, highly plastic material that appeared to be the same in all three samples. Laboratory testing indicated that the three samples had distinctly different engineering properties, as indicated in Table 1.

Table 1
Physical Properties of Visually Identical River Bottom Samples

Sample	Gs	LL	PL	PI	% sand	% silt	% clay	Class
MRA	2.76	110	37	73	1	74	25	CH
MRB	2.74	92	37	55	8	48	44	CH
MRC	2.74	77	31	46	16	40	44	CH

All three samples are classified as high plasticity clay with similar specific gravity (Gs) and similar plastic limit (PL). The grain size distribution varies significantly for MRA, which also has the highest liquid limit (LL). Figure 1 shows the cumulative grain size distribution curves for all three samples, Figure 2 shows the frequency grain size distribution curves, and Table 2 shows the median and mean grain sizes.

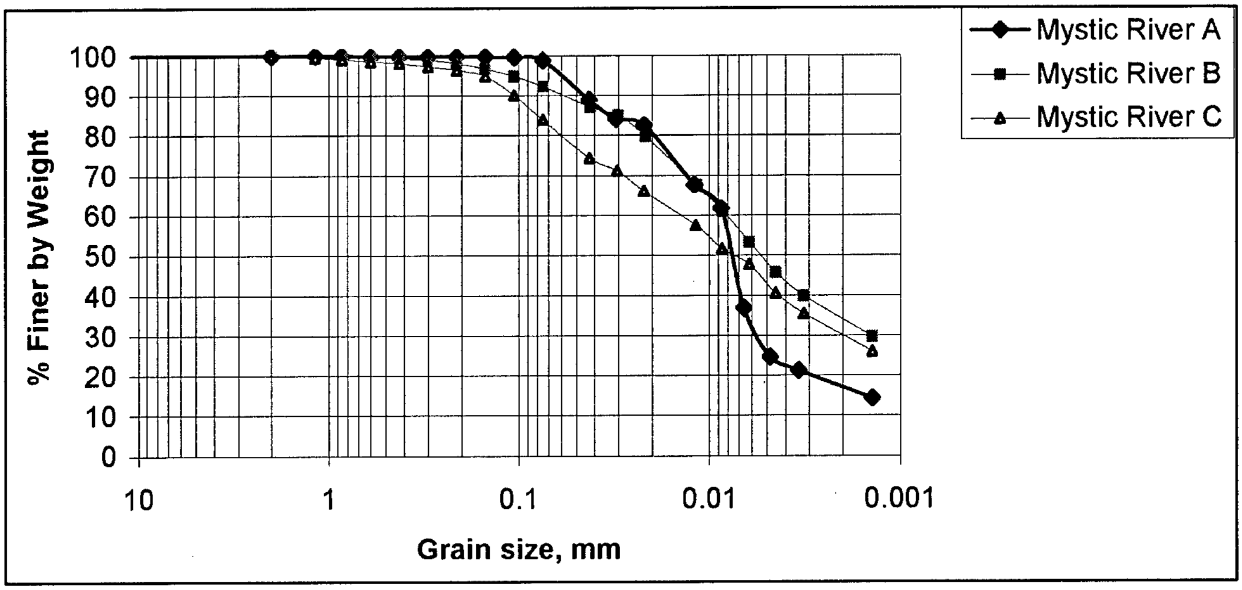

Figure 1: Cumulative grain size distribution (by weight) curves for river bottom samples

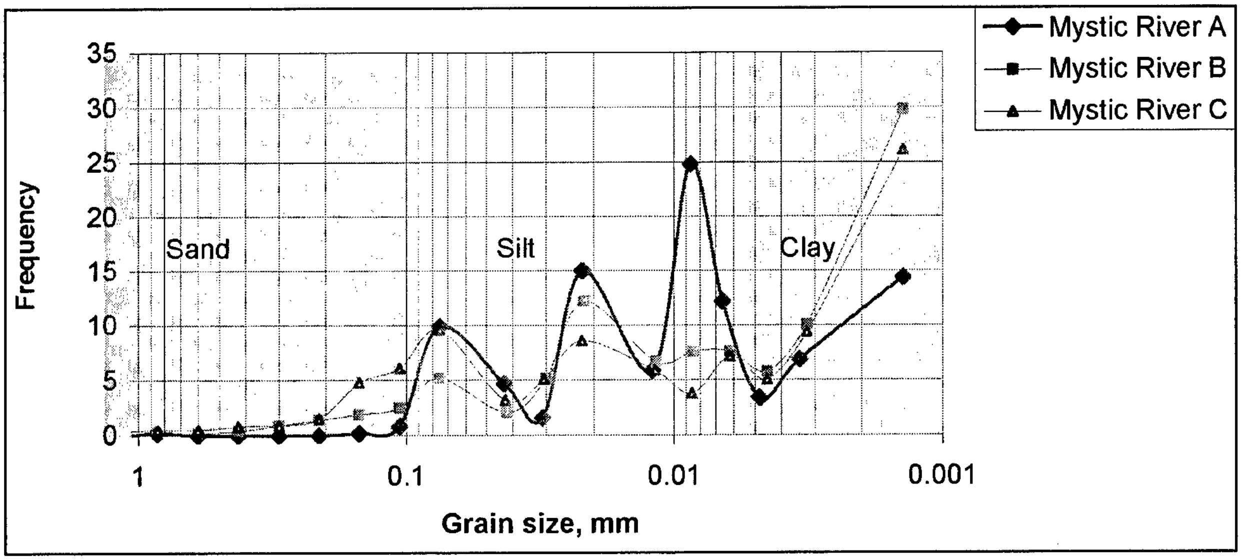

Figure 2. Frequency grain size distribution (by weight) curves for river bottom samples

Table 2 Median and Mean Grain Size (by weight) for River Bottom Samples		
Sample	**Median, mm**	**Mean, mm**
MRA	0.008	0.02
MRB	0.005	0.03
MRC	0.008	0.06

These curves show that the grain size distributions for samples MRB and MRC are similar, but MRA has a significantly different grain size distribution. MRA has a smaller clay size fraction (25 percent) and a higher silt size fraction (74 percent) than the other two samples. Based on the

median grain size (D_{50}) value alone, all three samples would appear to be virtually the same material, but the mean grain size indicates otherwise. The median grain size (D_{50}) for all three samples has a variance (σ^2) of only 0.000003 mm, while the mean grain size variance is much greater at 0.004 mm.

Although the materials would appear to be the same based on soil type classification, the engineering behavior of each material is unique. For example, Figure 3 shows the undrained shear strength curve for each material as a function of decreasing water content. For any given water content, there are three different shear strength values, varying from 3 to 25 psf (0.1 to 1.2 kPa). Undrained shear strength is a measurement of the ability of the soil to withstand imposed loading such as the weight of an overlying sand cap, for example. The higher the shear strength value, the higher the loading ability.

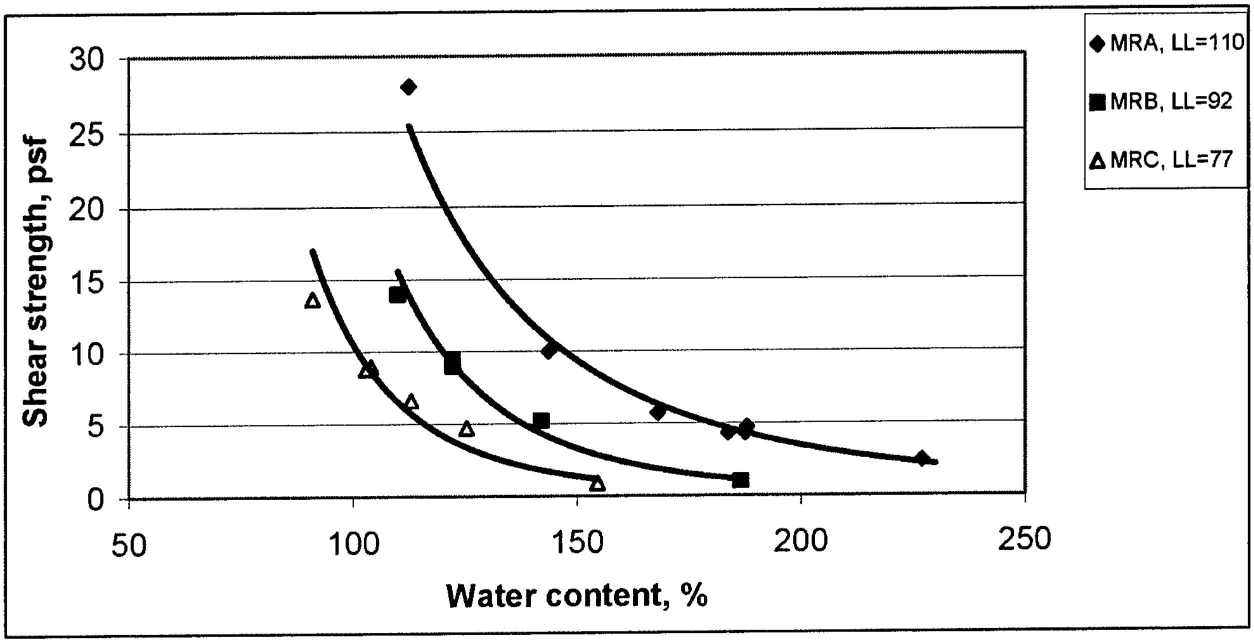

Figure 3. Undrained shear strength vs. water content on drying to the liquid limit

The ability to predict undrained shear strength in dredged materials is important to the geotechnical engineer responsible for analyzing subaqueous slope stability or designing engineered structures built with dredged material. For a simplistic example, based solely on the shear strength curves shown above where water contents exceed the liquid limits, a slightly steeper subaqueous slope geometry and/or a slightly larger overburden stress may be obtainable using material dredged from the upper reaches of the river (MRA). At water contents above the liquid limit, the materials with progressively less sand content have greater shear strength. The implication here is that each sample exhibits a slightly different engineering behavior, which would impact the material behavior after final disposal or placement. Spatial variability in dredged material properties could thus affect engineering decisions. The ability to choose or reject dredged materials based on their engineering behavior differences has obvious economic implications.

Dump Scow Samples. Three 5-gallon bucket samples were collected from different locations within a full barge of material dredged from a separate location in the Boston Harbor. A grab sample was taken from the surface material in the barge, and two clamshell bucket samples were obtained from within the barge material (SAIC 2000). The samples were analyzed and their physical properties are shown in Table 3. Figures 4 and 5 show the grain size distributions, and Table 4 shows the median and mean grain sizes.

Table 3
Physical Properties of Dump Scow Sediment Samples

Sample	Gs	LL	PL	PI	% sand	% silt	% clay	Class
Scow 1	2.33	77	37	40	11	57	32	MH
Scow 2	2.63	56	24	32	26	46	28	CH
Scow 3	2.63	40	35	5	43	36	21	ML

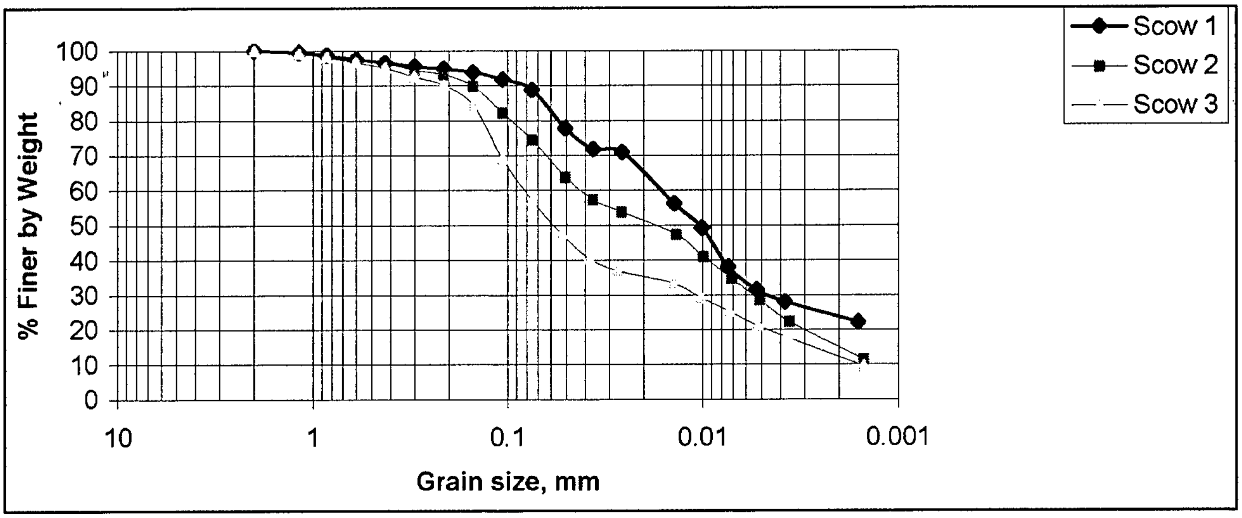

Figure 4. Cumulative grain size distribution (by weight) curves for dredged material samples taken from three points in the dump scow during one load cycle

Each sample taken from different locations within a single dump scow load has a progressively larger median grain size, mean grain size, and sand percentage. The liquid limits, plasticity indices, and fine grain percentage progressively decrease. Each sample also has a different soil classification. All three samples are fine-grained and visually appear to be identical.

Variability in physical properties such as Atterberg limits and grain size distribution has an impact on the engineering behavior of the dredged materials. Figure 6, based on the liquidity index (water content percent minus PL divided by PI), indicates that the material with the lowest liquid limit and highest sand content (Scow 3) has a slightly higher shear strength at water contents above its liquid limit than the other two materials. For example, if the end use of the dredged materials was to build an upland dike, the materials represented by the Scow 3 sample probably would exhibit higher slope stability (and factor of safety) at initial water contents above the liquid limit than the other two materials. It is also possible that a higher rate of strength gain with time (due to drying) would be observed in a Scow 3 dike if all three materials were initially deposited wetter than their respective liquid limits, although additional testing would be required to validate these engineering behavior assumptions prior to designing with the Scow 3 material.

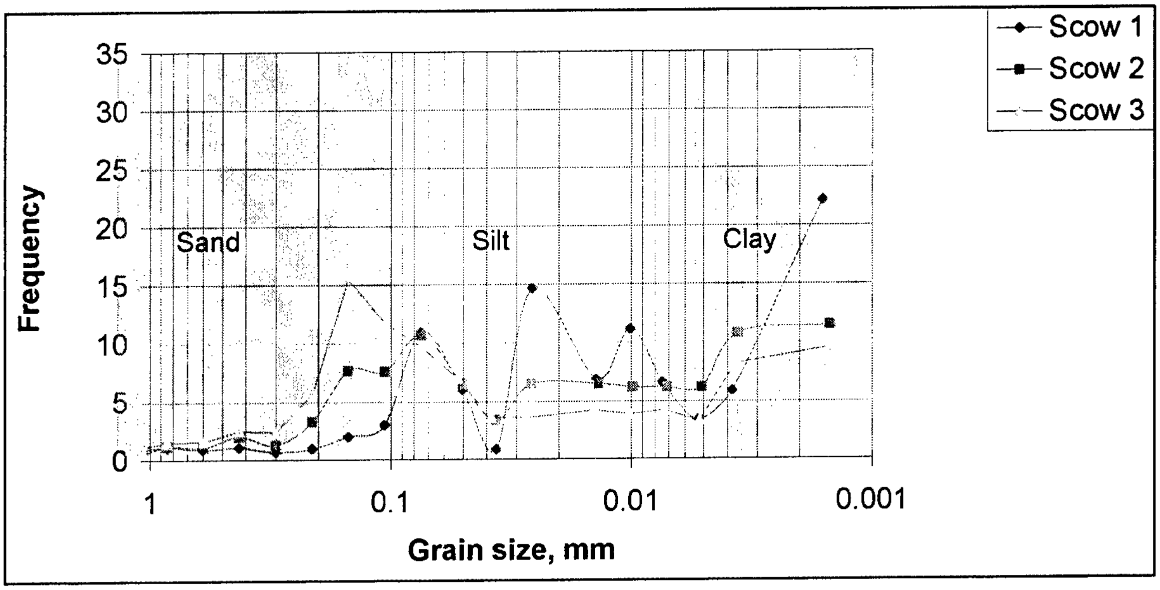

Figure 5. Frequency grain size distribution (by weight) curves for dredged material samples taken at three locations in the dump scow during one load cycle

Table 4 Median and Mean Grain Size (by weight) for Dump Scow Sediment Samples		
Sample	**Median, mm**	**Mean, mm**
Scow 1	0.01	0.069
Scow 2	0.02	0.095
Scow 3	0.06	0.13

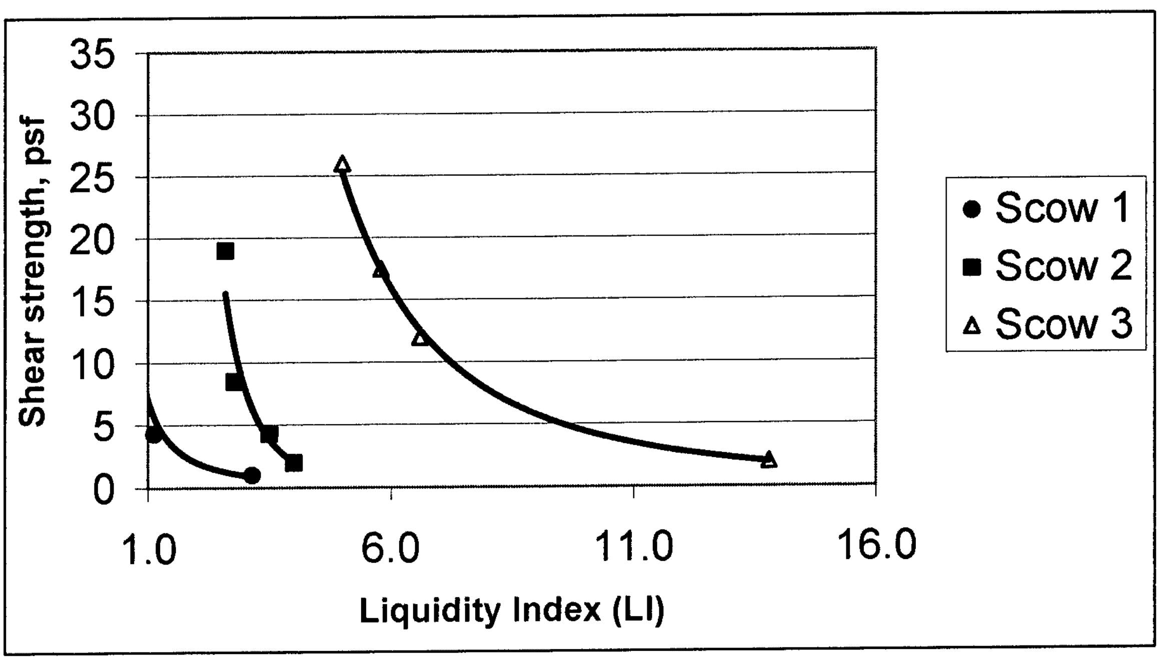

Figure 6. Undrained shear strength vs. water content on drying to the liquid limit

VARIABILITY DUE TO DREDGING OPERATION: In addition to the influence of spatial variability, there is uncertainty when predicting the geotechnical properties of dredged sediments during the dredging operation.

Hydraulic Suction Dredging. To observe the changes in properties between pre-dredged sediment and post-dredged sediment during suction hopper maintenance dredging, grab samples were taken in the Mobile Bay channel and on a hopper dredge. The Bay samples were taken within a 50-ft (16.5-m) radius with a hand-operated bottom dredger sampler in the surficial sediment inside the pre-dredged main navigation channel at water depths of approximately 40 ft (13.2 m). The hopper dredge sample was a hopper grab sample of material dredged within a 500-ft (165-m) reach of the pre-dredged samples during transport to an ocean disposal site.

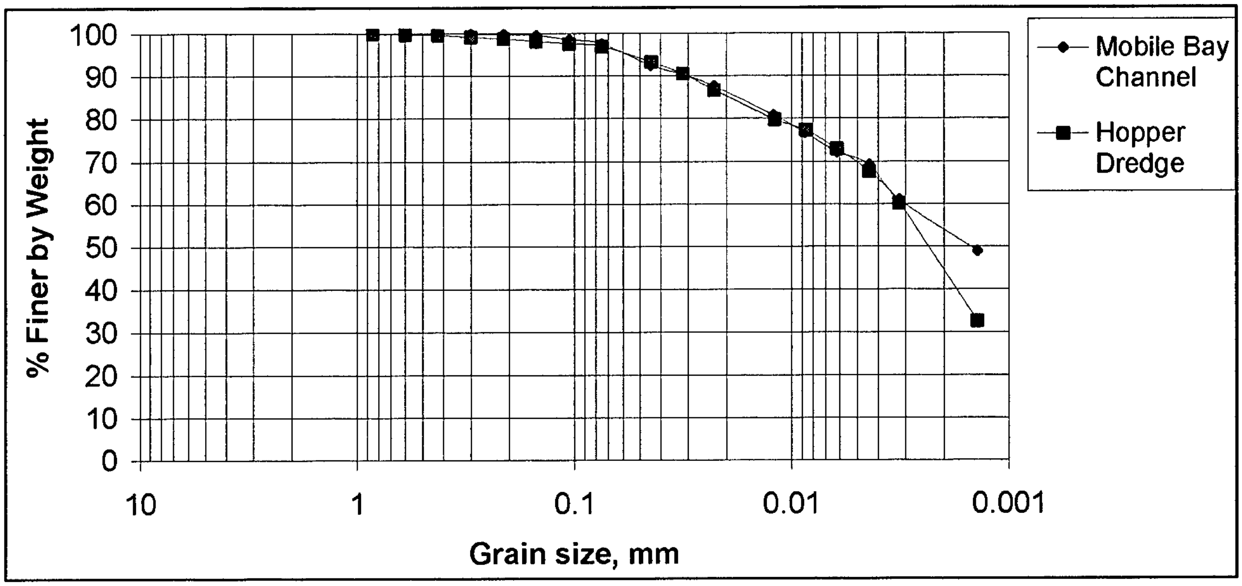

Figure 7. Cumulative grain size distribution (by weight) curves for dredged material samples taken prior to dredging (Mobile Bay Channel) and post-dredged (Hopper Dredge)

The pre-dredged and post-dredged materials had the same soil type classification, CH, with liquid limits within 7 percent of each other. The as-sampled water content of the pre-dredged material was 212 percent, and the as-sampled water content of the post-dredged material was 546 percent, indicating a solids bulking factor of 2 caused by hydraulic dredging (solids bulking = $\omega_{final} + 1 / \omega_{initial} + 1$).

The median pre-dredged grain size was 0.001 mm, and the post-dredged size was 0.002 mm. The mean pre-dredged grain size was 0.013 mm, and the post-dredged size was 0.018 mm.

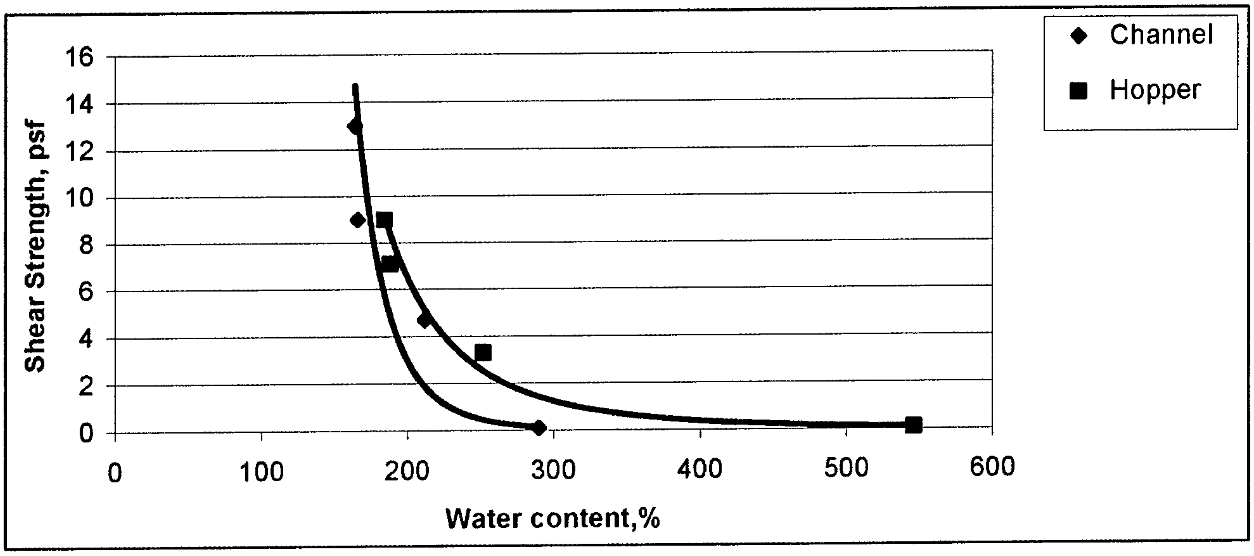

Figure 8. Comparison of pre-dredged and post-dredged vane shear strengths (to convert psf to kPa, multiply psf by 0.048)

The pre- and post-dredged vane shear strength curves shown in Figure 8 are similar. Since the difference in shear strength for a given water content is only approximately 2 psf (0.1 kPa), and both curves approach a similar shear strength value at the liquid limit, the shear strength variability is negligible.

Two major differences are evident in the pre- and post-dredged materials. Hydraulic dredging increased the water content from 212 percent to 546 percent, an increase by an approximate factor of 2.6. The other major difference is in the grain size distribution for the finest particles. Although the two samples had a similar sand percentage (3 percent), similar silt percentage (27 percent), and similar clay percentage (70 percent), the post-dredged sample had a 16-percent drop in the amount of fine clay in the size range between 0.003 and 0.001 mm. The hydraulic dredging operation may have removed the finest clay particles, or other factors such as sampling locations, normal grain size variability, and/or limited sampling data may have influenced the particle size discrepancy.

Mechanical Dredging. To observe the pre- and post-dredged sediment property changes due to mechanical dredging, a composite sample from the pre-dredged Mystic River was compared to a composite sample from the dump scow which was filled with clamshelled material from a downstream dredging location. Although the spatial variability for these samples was discussed above, and there is a strong likelihood that a composite sample is not a representative sample, the two composite samples are compared in Figure 9, which is the grain size cumulative distribution.

A paired t-test (a statistical method useful for examining changes which occur before and after an experiment) indicates that there is a statistically significant difference between the two samples. The post-dredged material is coarser-grained and has less fines than the pre-dredged material, which may be due to the dredging method, spatial variation, or other influences.

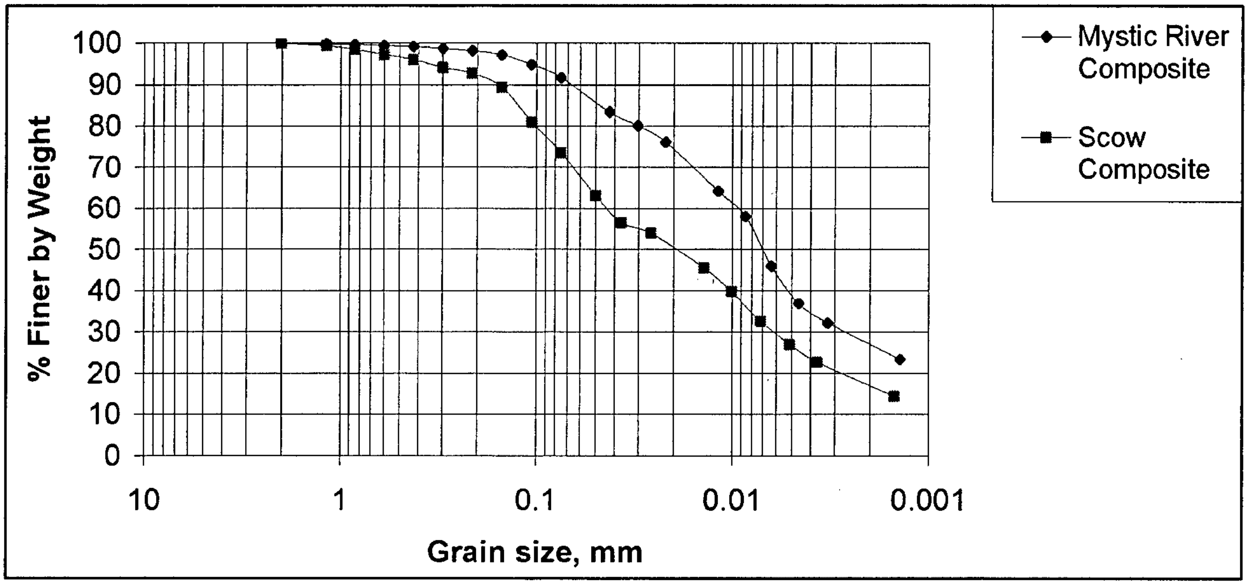

Figure 9. Cumulative grain size distribution (by weight) curves for pre- and post-dredged material samples after mechanical dredging

VARIABILITY DUE TO DREDGED MATERIAL PLACEMENT: In addition to the influence of spatial variability and dredging operations, the properties of dredged material may change depending on their final placement or disposal. Variability will be encountered in the placement process due to the methods and equipment used. For example, sediments transported via pipeline are layered differently than those placed by clamshell bucket. Also, the placed sediment likely mixes with native sediment, which changes its properties and subsequent engineering behavior.

Open Ocean Placement. To make a general comparison between properties of pre-dredged and post-placed sediments deposited at an open (unconfined) ocean site, pre-dredged material sampled from the Gulf Coast's Mobile Bay was compared to previous data where similar material was placed at an open ocean site near the entrance to Mobile Bay (Davis et al. 1999). The fine-grained material was dredged with a clamshell bucket dredge, transported via split-hull barge scows, and dumped through an approximate 30-ft (10-m) water column onto a sandy ocean floor, which had a mean grain size (by weight) of 0.21 mm. Tables 5 and 6 list some of the geotechnical properties of the pre-dredged and post-placed samples. Figure 10 shows the grain size distributions.

Table 5
Median and Mean Grain Size (by weight) for Ocean-Placed Sediment Samples

Sample	Median, mm	Mean, mm
Pre-dredged (Mobile Bay)	0.001	0.013
Post-placed (open ocean)	0.015	0.077

Table 6
Physical Properties of Ocean-Placed Sediment Samples

Sample	Gs	LL	PL	PI	% sand	% silt	% clay	Class
Pre-	2.73	156			3	27	70	CH
Post-	2.65	69	26	43	27	37	36	CH

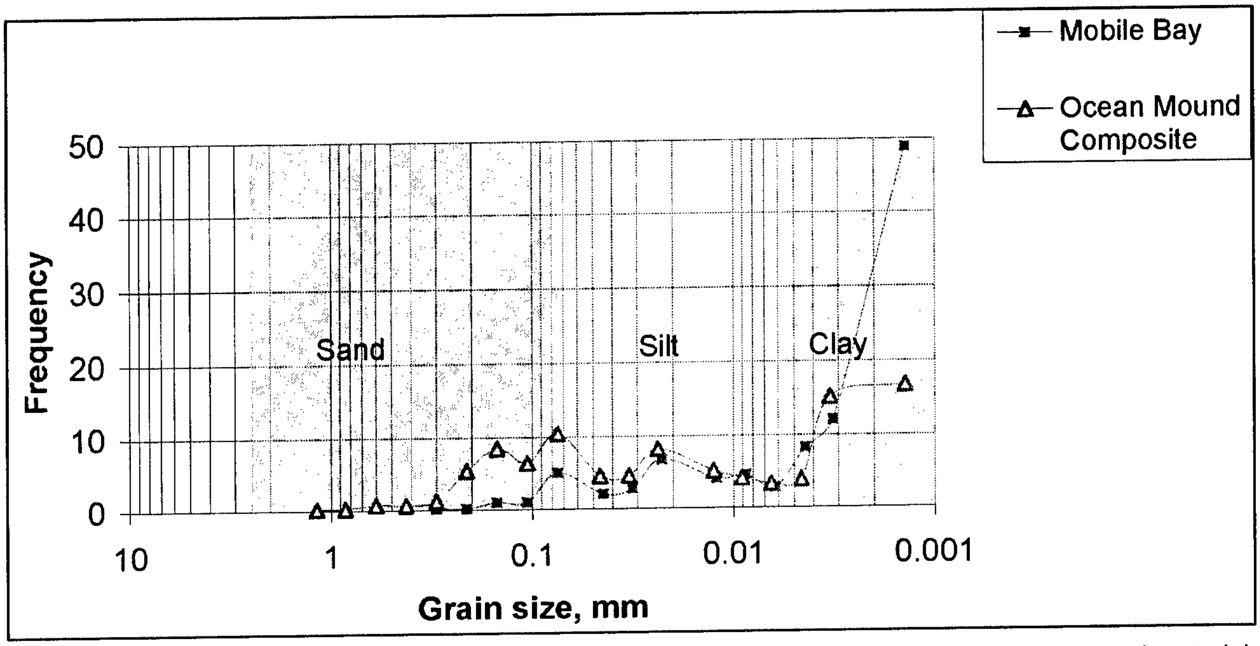

Figure 10. Frequency grain size distribution (by weight) curves for pre-dredged and post-placed material samples

The two curves have similar particle size frequency distributions in the coarse sand and fine silt ranges, but vary in the fine sand and fine clay ranges. The variation in the fine sand percentage is likely due to mixing with the native sandy sediment, which has a mean size of 0.21 mm as reported by Davis et al. (1999). The variation in the fine clay percentage is likely due to loss in the water column during placement, or from surficial erosion as reported by Gailani et al. (2001).

Confined Aquatic Placement. Property variability has also been observed in pre-dredged and post-placed sediments placed in a contained subaqueous pit. For the previously referenced Boston Harbor project, the subaqueous cell M2 received material from the Mystic River channel mechanically dredged in the relative vicinity of surficial grab samples MRA, MRB, and MRC. The dredged material was placed using split-hull scows dumping through approximately 25 ft (8.2 m) of water to the top of the subaqueous cell surface. Figures 11 and 12 compare composite samples MRA, MRB, and MRC to the dredged material subsequently placed in subaqueous cell M2.

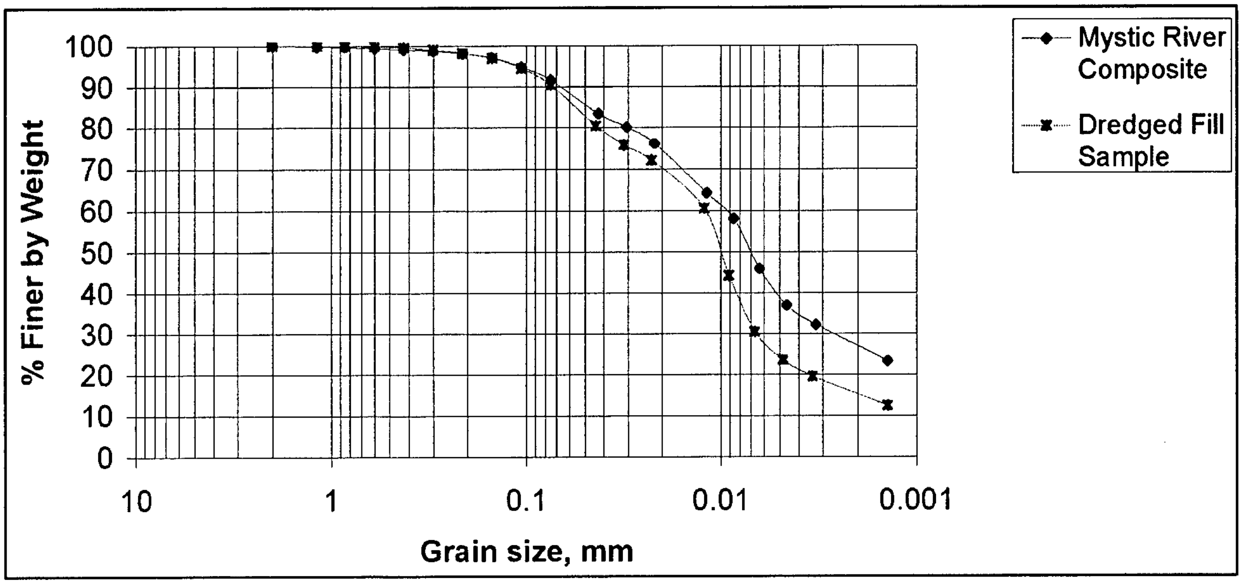

Figure 11. Cumulative grain size distribution (by weight) curves for pre- dredged and post-placed material samples after mechanical dredging and dump scow placement

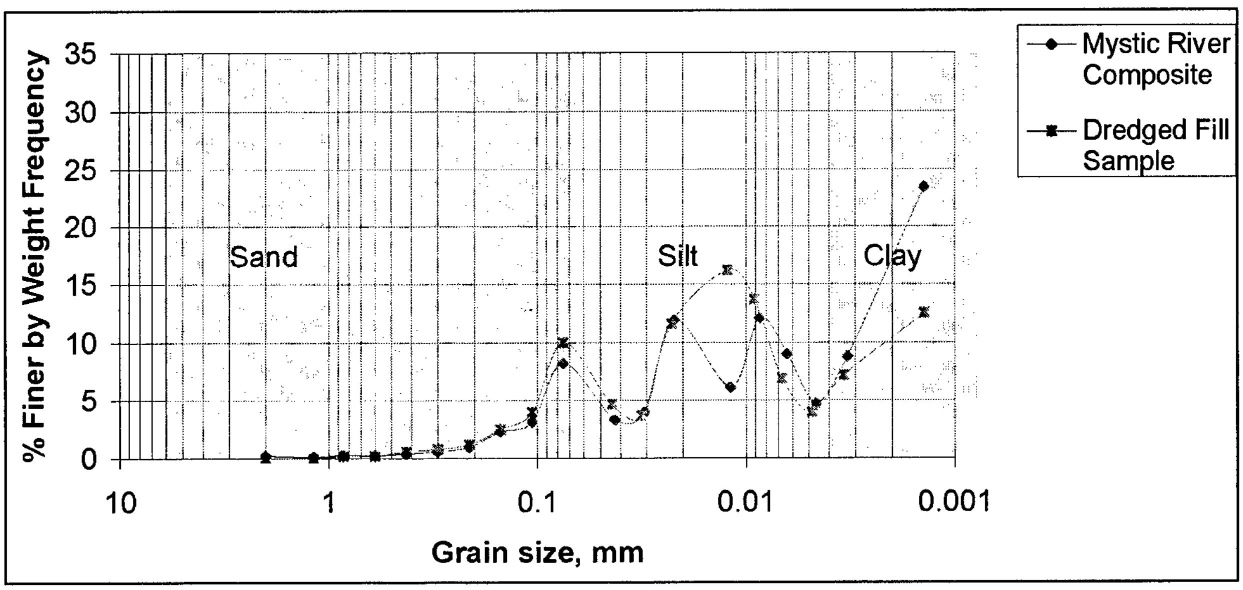

Figure 12. Frequency grain size distribution (by weight) curves for pre- dredged and post-placed material samples after mechanical dredging and dump scow placement

The Atterberg limits of the two materials are similar (LL = 90 and PL = 34, plus or minus 2). The grain size distribution curves are similar except in the fine silt and fine clay ranges. The dredged fill placed in the subaqueous pit contains 10 percent more fine silt and 10 percent less fine clay material compared to its pre-dredged composition. Numerous reasons may be conjectured, including stripping of the fine clay fraction during the dredging and dumping operations, silting sediment from the channel into the pit, erosion processes, or normal sampling variations.

At a coarser-grained dredged material site on the Pacific coast, sandy sediment from the Los Angeles River was grab-sampled prior to clamshell dredging and split-hull dump scow placement onto the bottom of the North Energy Island fine-grained subaqueous pit. A cap (approximately 3 ft (1 m) thick) of sandy dredged material was placed through approximately 45 ft (14.8 m) of water onto a very soft silty-clay foundation material, and some mixing of the dredged fill and foundation materials was expected. Figures 13 and 14 show the grain size distribution curves for the pre-dredged sediment, post-dredged fill, and original foundation materials, and Tables 7 and 8 show selected physical properties.

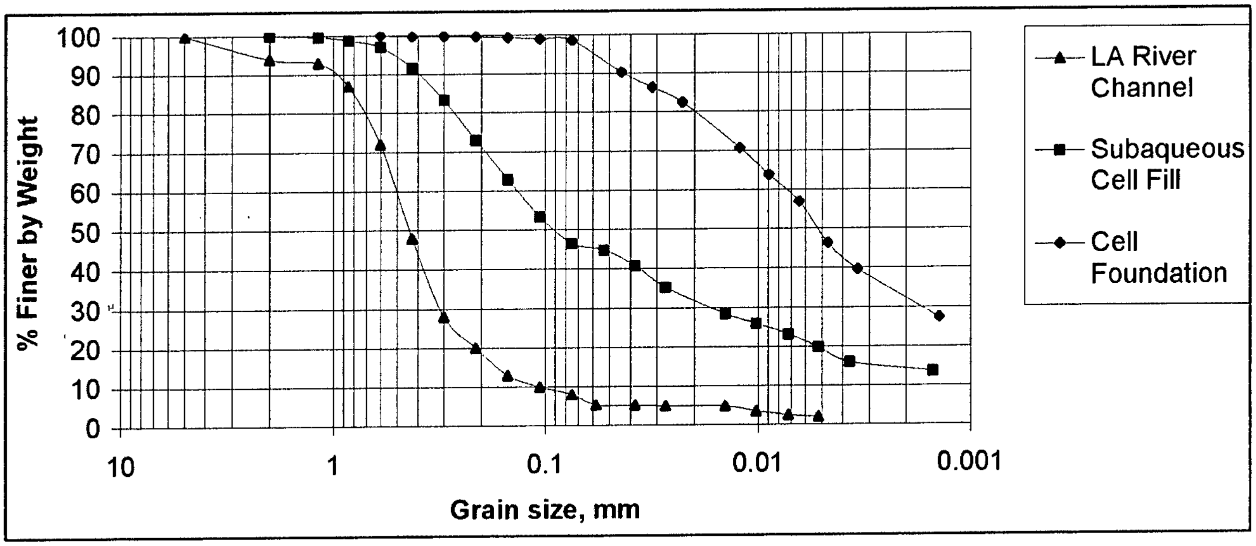

Figure 13. Cumulative grain size distribution (by weight) curves for pre- dredged, post-placed, and original foundation materials after mechanical dredging and dump scow placement

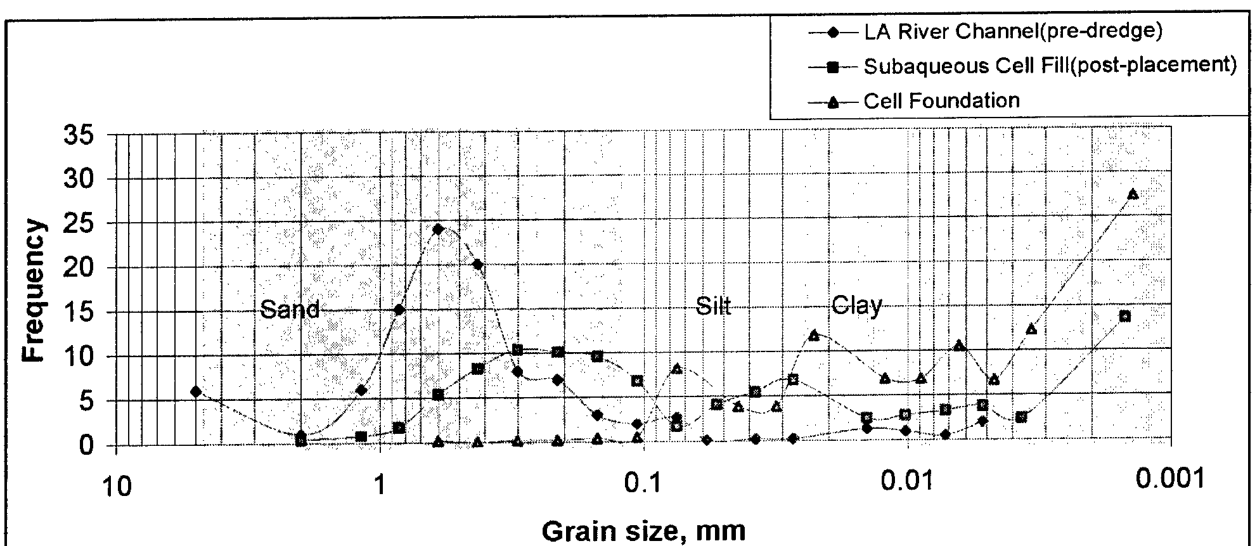

Figure 14. Frequency grain size distribution (by weight) curves for pre- dredged, post-placed, and original foundation materials after mechanical dredging and dump scow placement

Table 7
Physical Properties of Sediment Grab Samples

Sample	Gs	LL	PL	PI	% sand	% silt	% clay	Class
LA Riv	2.66	-	-	-	90	10	0	SP
Fill	2.67	-	-	-	54	27	19	SM
Foundation	2.75	71	36	35	2	48	50	MH

Table 8
Median and Mean Grain Size (by weight) for Sediment Grab Samples

Sample	Median, mm	Mean, mm
LA River material	0.42	0.79
Dredged fill material in pit	0.09	0.18
Foundation material	0.005	0.018

The original sediment appears to have been transformed from a poorly graded sand into a silty sand material by the time it was deposited into the subaqueous pit and subsequently sampled. Several reasons may account for this change. Spatial particle size distribution variability in the pit may have occurred as the coarser-grained material filled the pit bottom prior to the finer-grained material (winnowing), sampled materials may have a high degree of grain-size heterogeneity, or sediment mixing with the soft fine-grained foundation material may have occurred. The most likely scenario was sediment mixing and displacement of the very soft foundation material. Modeling the foundation material's stress–displacement as a function of cap stress (overburden weight) demonstrated upward and outward displacements of the soft foundation material at the sideslope interfaces with the dredged fill material (Lee 2001).

Regardless of the reasons for material property changes due to dredging operations, the lessons illustrated here are that those changes do occur and must be accounted for in proportion to the importance of quantifying subsequent engineering behavior changes. It may not be important to know that dredged fill grain size distributions may change unless quantifying the subsequent engineering behavior in that fill is important. As an example, porosity is only one of the many material properties influenced by grain size distribution variability. Changes in porosity may not need to be known for routine maintenance dredging, but computer models for water quality and environmental fate depend on accurate porosity values.

VARIABILITY DUE TO DEFINITIONS: In addition to the changes in geotechnical properties and engineering behavior in dredged materials, there are uncertainties in assigning property parameters based on possible alternate definitions of those parameters. For example, the physical property of water content may be defined in two or three different ways, depending on the test or reporting method.

The standard method for water content (ASTM 1998) calculates the weight of water divided by the weight of dry solids. Alternate but commonly used methods calculate the weight of water divided by the total wet weight, or by a volumetric basis. Figure 15 compares three definitions of water content referenced to the geotechnical standard (ASTM method):

$$\text{ASTM water content} = \omega = Ww/Ws \quad (1)$$

$$\text{Wet (total) weight water content} = w = Ww/W \quad (2)$$

$$\text{Volumetric water content} = \theta = Vw/V \quad (3)$$

where Ww = weight of water, Ws = weight of dry solids, W= wet weight, Vw= volume of water, and V= total volume.

To compare the differences in calculated values,

$$w\% = 100(\omega\%) / (\omega\% + 100) \quad (4)$$

$$\theta = e / 1+e \quad \text{where } e = \text{void ratio} = \omega \, Gs \quad (5)$$

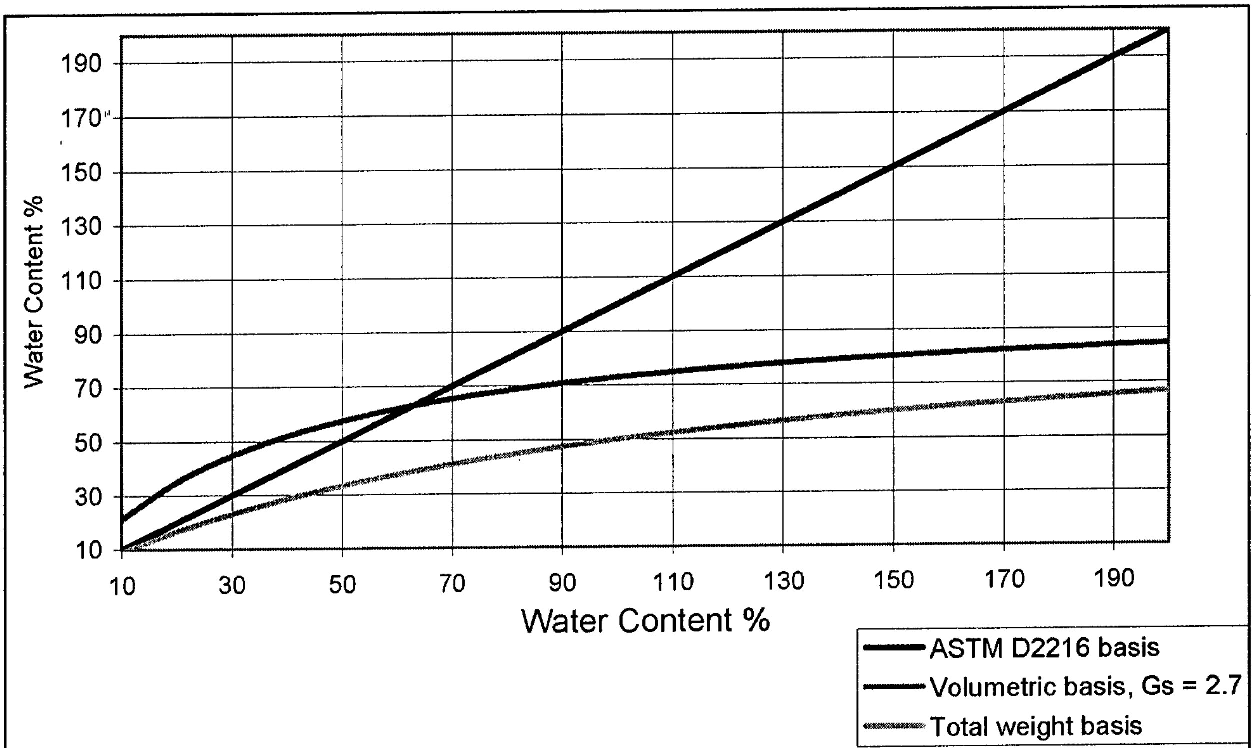

Figure 15. Comparison of water content definitions

Grain size distributions based on volume instead of weight measurements will introduce parameter variability when the two methods are compared. For example, Figure 16 shows gradation curves for a sandy dredged material tested on both a weight basis and a volume basis. The volume basis curve indicates a slightly coarser material, with a 0.1-mm difference in the median particle sizes.

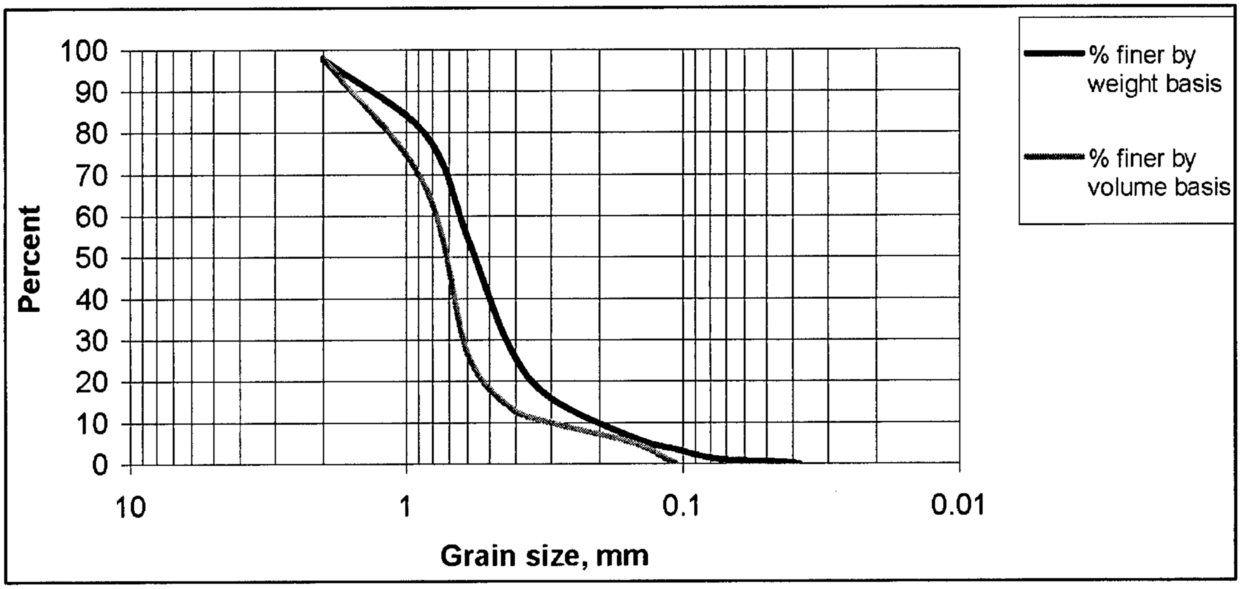

Figure 16. Variability between cumulative grain size distributions (weight vs. volume basis) for identical materials

SUMMARY: Accurately predicting geotechnical property changes in the sediment and dredged material cycle (pre-dredged, post-dredged, pre-placement, and post-placement) involves a degree of uncertainty. Assigning parameters for sediment and dredged material properties may be challenging due to differences in reporting methods and lack of available information on material characteristics during any given stage of the dredging operation.

Comparisons of material physical and engineering behavior properties before, during, and after selected dredging operations show that quantifiable changes occur and those changes may depend on unknown relationships in the dredging process. Acquiring better understanding of the relationships between changed material properties and dredging operations will eventually enable better predictions for economical project planning, permitting, design, construction, operation, and management.

ADDITIONAL INFORMATION: Questions about this technical note can be addressed to Mr. Landris T. Lee (601-634-2661, Fax 601-634-3453, e-mail: *Landris.T.Lee@erdc.usace.army.mil*). This technical note and associated research work were funded by the Dredging Operations and Environmental Research (DOER) Program 12B Nearshore Focus Area Work Unit 33292 titled "Geotechnical Properties of Dredged Material." Program Manager of the DOER is Dr. Robert M. Engler (601-634-3624, *Robert.M.Engler@erdc.usace.army.mil*), and the Nearshore Focus Area Manager was Dr. Joseph Z. Gailani (601-634-4851, *Joseph.Z.Gailani@erdc.usace.army.mil*). This technical note should be cited as follows:

> Lee, L. T. (2004). "Variability in dredged material geotechnical properties," DOER Technical Notes Collection (ERDC TN-DOER-D-X), U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi. *www.wes.army.mil/el/dots/doer/*

REFERENCES:

American Society for Testing and Materials (ASTM). (1998). "Standard test method for laboratory determination of water (moisture) content of soil and rock by mass," Designation D2216-98, American Society for Testing and Materials, West Conshohocken, PA.

Davis, J.E., Stauble, D.K. and Rollings, M.P. (1999). "Construction and monitoring of a mixed-sediment mound offshore of Mobile Bay, Alabama," *DOER Technical Notes Collection* (ERDC TN-DOER-N6), U.S. Army Engineer Research and Development Center, Vicksburg, MS. *www.wes.army.mil/el/dots/doer*

Department of the Army. (1983). "Dredging and dredged material disposal," Engineer Manual EM 1110-2-5025, U.S. Army Corps of Engineers, Washington, DC.

Gailani, J.Z., Kiehl, A., McNeil, J., Jin, L. and Lick, W. (2001). "Erosion rates and bulk properties of dredged sediments from Mobile, Alabama," *DOER Technical Notes Collection* (ERDC TN-DOER-N10), U.S. Army Engineer Research and Development Center, Vicksburg, MS. *www.wes.army.mil/el/dots/doer*

Lee, L.T. (2001). "Evaluation of the dredged material geotechnical properties for the Los Angeles River Estuary Dredging and Aquatic Capping Pilot Study." Letter Report to the Los Angeles District Corps of Engineers, 31 December 2001.

Myre, P.L., Walter, P.J., and Rollings, M.P. (2000). "Geotechnical evaluation of sediment data collected in Boston Harbor CAD Cells." *Proceedings, WEDA 2000.* Warwick, RI.

Science Applications International Corporation (SAIC). (2000). "Geotechnical investigation of CAD cells in the Boston Harbor Navigation Improvement Project," SAIC Report No. 503, Contract No. GS35F4461G, Science Applications International Corporation, Newport, RI.

Scott, R.F. (1963). *Principles of soil mechanics.* Addison-Wesley Publishing Co., Palo Alto, CA.